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STRUCTURAL DIVISION

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STRUCTURAL APPLICATION OF HIGH-STRENGTH BOLTS

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The entire growth of engineering knowledge with respect to the use of metal construction, which plays such an important part in modern living today, can almost be encompassed within the one hundred years which have elapsed since the founding of the American Society of Civil Engineers. While the use of rivets and bolts in the joining of metal components had been part of the craftsman's art for centuries, engineering concepts as to the behavior of such joints, by means of which their strength could be evaluated for the design of structures, were probably first applied in the construction of the Britannia and Conway tubular bridges about the middle of the Nineteenth Century.

Of necessity, in the beginning these concepts were supported by test data obtained only from very small specimens. Considering the very simple and not altogether accurate testing methods used, it is remarkable that these data agree as well as they do with those of more recent investigators.

It is interesting to note that the contribution to the strength of a joint made by the "friction produced by the cooling of red-hot rivets" was recognized by at least one writer, even a century ago. He observed that, at working loads, his joints acted by friction alone. Nevertheless the classical concept of a riveted or bolted joint almost from the start has been that of adjacent plies loaded in opposite directions and held together by virtue of the shear strength of the fastener.

In the case of riveted connections this resistance to applied loading is generally assumed to take place with little if any slip, because the forging of the rivet has substantially filled the rivet hole. Likewise, the use of turned bolts in reamed holes is also assumed to control the slip between the connected parts within tolerable limits, although hole clearances up to 1/50" are permitted in fabrication. In connections where slip is of less consequence, it has long been the practice to permit the use of unfinished bolts in holes punched or drilled to a size 1/16" greater than that of the bolts themselves.

The accepted use of high-strength bolts, prestressed to such a tension that friction between the connected parts alone can be relied upon to transfer the stress from one member to another, is a development which has taken place in the field of bridge and building construction only within the past five years. Several factors have served to stimulate this development.

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In the first place, it was discovered that the use of hardened washers under the nut and the bolt head made possible the presence of clamping forces greatly in excess of the best that could be achieved through the shrinkage of hot rivets upon cooling, and that these clamping forces are sustained without significant relaxation even after hundreds of thousands of loading cycles.

In the case of bridges and other dynamically loaded structures, the demonstrated superiority of highly-prestressed high-strength bolts in providing a smoother stress path, thus materially improving the fatigue strength of the joint, offers a distinct advantage over riveted construction.

The use of high-strength bolts for the field connections of bridges and buildings involves no re-taining of drafting room or fabricating shop forces, nor any replacement or rearrangement of existing shop equipment and fabricating practices.

Costwise, their use is competitive with that of riveting. The bolts themselves are much more expensive than undriven rivets, but the difference is largely, and in some cases completely, offset by lower installation costs. Even were this not so, the present shortage of riveters in many parts of the country still would suggest a need for this newer type of fastener, the proper installation of which requires only a minimum of steel worker training.

In the early stages of the investigation covering the use of high-strength bolts sponsored by the Research Council for Riveted and Bolted Structural Joints, it was realized that laboratory tests conceivably might not include all of the factors affecting their behavior in dynamically loaded railroad and highway bridges. The joints of such structures are subject not only to fluctuation in loading but also, concurrently, to vibrations of varying amplitude and frequency. Accordingly, in 1948 the research staff of the Association of American Railroads arranged with several railroads to replace with high-strength bolts over 1,000 existing rivets in a number of joints of 12 different bridges, where trouble had been encountered keeping rivets tight because of excessive vibration and other unusual service conditions. In several of these structures maintenance crews have had to re-drive a certain number of loose rivets each year.

It had been the practice with some of the railroads for the division forces to temporarily replace rivets, found to be loose by the bridge inspectors, with ordinary carbon bolts. Eventually these bolts in turn would be replaced by new rivets, installed by the steel bridge gang when the accumulated number to be driven was sufficient to justify bringing a compressor and riveting equipment to the site. In the meantime it often would be necessary to re-tighten the temporary bolts, since they were incapable of retaining their initial tension for any extended period under the service conditions.

In each case included in the field test program all of the rivets in a joint were replaced, one at a time, by high-strength bolts of the same nominal diameter. These bolts have been inspected periodically and, after four years, still retain their full clamping force. Meanwhile the rivets in similar joints on the same structures (sometimes at the other end of the same member) have continued to work loose.

In one case, where common washers were originally installed with the high-strength bolts, the bolts did not stay tight. However, ever since the common washers were replaced with hardened washers nearly four years ago the bolts have maintained their initial prestress.

Some bolts were installed in jagged holes which had become enlarged as a result of the frequent backing out of loosened rivets. Wherever two hardened washers were placed under the head and nut of these bolts, to prevent deflection in the enlarged holes, the bolts retained their full clamping force.

In all of these installations the friction created in the threads by the high initial bolt tension alone was sufficient to prevent any loosening of the nut. No self-locking type of nut or washer was used and the threads were not burred after the nuts had been tightened.

In general the bolts used in this program were tightened to develop a tension stress on the mean thread area equivalent to approximately 85 percent of the specified yield point stress, or 72,000 psi. The bolts in several of the joints, however, were deliberately tightened well beyond the yield point stress. This excessive amount of prestress did not appear deleterious however; the bolts so tightened have been functioning satisfactorily upward of four years now without exhibiting any visible evidence of damage or impaired clamping force.

In order to study the use of high-strength bolts in cold climates, existing rivets were replaced by such bolts in several floorbeam hanger connections on riveted bridge trusses situated where the temperatures fall to at least 40° below zero. These bolts have now been in place for two winters and have proven entirely satisfactory for that time.

The cost advantage in the use of high-strength bolts on bridge maintenance is quite apparent. The transportation cost of driving equipment, per re-driven rivet, or necessity is high, because of the limited number and scattered location of rivets involved, even when the riveting operation is postponed as long as possible by the temporary substitution of ordinary bolts. The required tightening specified for high-strength bolts, on the other hand, can be achieved with manually operated wrenches.

While this method of installation offers the best economy when only a few scattered bolts are required at some remote site, it would be unnecessarily expensive for general use on building construction. Here the use of air impact wrenches not only reduces the required physical effort to a minimum and saves considerable time, but also admits of a simple yet remarkably effective bolt tightening control.

These pneumatic impact wrenches are only slightly heavier than the hand hammers required for driving rivets of the same nominal diameter. They require but a single operator and are about as portable as riveting hammers.

The torque required to tighten the nut to the desired tension, after the air motor has spun it down until it is first seated, is provided by means of a very rapid succession of blows delivered normal to radial lines passing through the bolt centerline. The blows are delivered simultaneously on opposite sides of the bolt; their reactions are balanced

and the physical effort required of the operator is considerably less than that involved in driving rivets. Furthermore, this effort need be sustained for only a fraction of the time involved in driving a rivet.

At a normal operating air pressure of say 80 to 90 pounds about five seconds is required after the nut first seats before it has been turned to the desired tightness. Depending upon the size of bolts being installed, as many as six wrenches can be served by a single 160 cm compressor.

It is this relationship of air pressure to nut-tightening effort which has provided the most effective bolt tension control thus far developed. By inserting a pressure regulator in the air supply line to each wrench, the wrench can be made to "stall" when the desired bolt tension has been achieved. Naturally, at this reduced pressure the tightening time is somewhat extended — from perhaps five seconds to about ten seconds depending upon the size and type of wrench — which places less of a premium on operator reaction time for the controls. At the point of "stall" the wrench continues to impact, but lacks the power to deliver a substantially larger torque. The point may be detected by a noticeably heavier vibration in the wrench. At this point there is no visible turning of the nut and the tightening socket on the wrench tends to recoil after each blow.

These wrenches are capable of tightening bolts of more than one nominal diameter, although more than one wrench size would be required to operate effectively over the entire range of bolt diameters encountered in bridge and building construction. Even for any one given diameter the amount of torque required to produce a specified bolt tension can vary somewhat, depending upon the condition of the threading.

Table III, given in the Research Council's Specification for the Assembly of Structural Joints Using High Tensile Steel Bolts, attempts to correlate required bolt tensions with corresponding equivalent pound-feet of torque, for various bolt sizes. In a footnote it is stated that these torque values are experimental approximations. A number of devices have been developed whereby the air pressure at the wrench can be adjusted so that the desired bolt tension is provided without reference to any intermediate measure of torque. Where these devices have been used, operators with no prior experience have been able to consistently obtain entirely satisfactory results. Using this technique, all of the variables — wrench capacity, bolt size and length, and condition of the threads — which affect bolt tightness are brought into proper balance in a single operation.

One of these devices permits the bolt to be tightened against the parallel faces at the ends of a hollow cylinder, in which the bolt had been inserted. The clamping force delivered to the cylinder by the tightened bolt can be read by means of electric resistance strain gauges and an indicator. Another device is so constructed that a bolt of the size and character to be installed at the site is tightened against an enclosed volume of fluid, the resulting pressure in which — converted to equivalent bolt tension — is read directly on a pressure gauge.

Bolts tightened with impact wrenches adjusted by these devices have been found to provide consistently accurate amounts of prestress when checked with a torque wrench. For this reason the inspectors' concern

has been more with the calibration of the impact wrenches and, subsequently, with maintaining it throughout the day, than with spot-checking the finished work with a torque wrench.

Some misunderstanding has been reported as to the intent of Section 4(b) of the Council's Specification. Attempts have been made to control the bolt prestress to precisely that specified in Table III — no more and no less. The tabulated tension values — 90 percent of the minimum specified elastic proof load of the bolts — are calculated to develop nearly the maximum clamping force that can be expected of the bolts. While no useful purpose is served when a bolt is strained beyond (rather than up) to its elastic limit, numerous field and laboratory tests have indicated that no damage is sustained by bolts tightened well beyond their elastic proof load. They still are capable of providing a clamping force limited only by the elastic properties of the bolt. Since the minimum specified breaking strength of the bolts is not reached until a tension in excess of 150 percent of the values given in Table III have been applied, too meticulous attention to an upper limit of prestress is unnecessary and only served to increase the erection cost.

Of course the use of a pneumatic impact wrench does entail some noise. During the short interval of time when the wrench is spinning the nut into bearing against the hardened washer the noise from the wrench ordinarily would be masked out by the level of noise incident to other construction operations. In fact the much sharper sound which follows when the nut has seated, likewise may be obscured by many common construction noises. The maximum noise level of the wrenching operation has been described as approximately one-half that of an ordinary riveting hammer. Its duration likewise is only half that required to drive a rivet. It is not without significance that many of the projects using high-strength bolts which have already been completed, or which are contemplated for construction in the immediate future, have been additions to hospitals where much study was given to this aspect of the problem.

Few building connections are subject to the dynamic loading and vibration which are characteristic of railway and highway bridges. Hence the superior fatigue strength characteristics of connections made with high-strength bolts loses much of its appeal in ordinary building construction. Nevertheless, as a means of relieving the pressure on a currently inadequate supply of trained riveters, economically and with a minimum of change in existing practices, the high-strength bolt has much to offer, as is evidenced by the number of structures which have been, or are being erected using them in the short time since their possibilities were first fully realized.

One of the first buildings to be constructed utilizing substantially the same techniques as that now recommended by the Council was a 14-story hospital for the University of Illinois, designed by Holabird and Root and Durgée of Chicago, Illinois. At the time the present Specification for Quenched and Tempered Steel Bolts, Serial Designation A-325 had not been accepted by the American Society for Testing Materials, and somewhat stronger and more expensive bolts were used in lieu of those now recommended. These bolts had to be manufactured to order and delays were experienced in delivery so that some additional

erection cost was involved. Nevertheless, the excess of cost over that which would have been entailed had field rivets been used, has been reported as between \$6.00 and \$7.00 per ton of steel erected.

Also included in recent bolted hospital construction have been the first eleven stories of a 21-story addition to the Mayo Clinic at Rochester, Minnesota, designed by Ellerbe and Company of St. Paul, Minnesota; a 21-story building for the Mayo Memorial Medical Center at the University of Minnesota, designed by C. H. Johnston, also of St. Paul; the 15-story General Hospital for the University of Oregon Medical School, designed by Lawrence, Tucker and Wallmann of Portland, Oregon; and the 13-story Johns Hopkins hospital building in Baltimore, designed by James R. Edmunds of Baltimore.

A complete tabulation of all the structures assembled with high-strength bolts in the past few years since their use was first proposed is not possible. One or two representative installations should suffice to develop a fair picture of the increasing popularity of this newest of fastening technique.

The new Aluminum Company plant at Sandow, near Rockdale, Texas, comprising some 25 industrial shed-type buildings will require approximately 100,000 high-strength bolts. These buildings, designed by the Aluminum Company's own engineering department, are one story high. The roof trusses span 60, 80 and in some cases, 100 ft.

Some 10,000 tons of structural steel will be required to complete a large jet engine manufacturing plant for the Chrysler Corporation at Utica, Michigan. Also included in the project is a much smaller 3-story frame for a power house. Plans for the construction were prepared by Albert Kahn Associated Architects and Engineers, Detroit. All primary connections will use A-325 bolts. Secondary connections such as purlins, sash angles, etc., will use ordinary unfinished bolts as would have been the case had the principal connections been riveted. The size of the large one story building was such that considerable planning was justified in organizing the erection forces for the new bolting technique. The steel was erected using one pin and one fitting-up belt in each connection, in the usual manner. The final bolts were installed by steel workers whose task was completed when these bolts were made snug with an ordinary handwrench. Since there were a great many repetitions of more-or-less identical connections, each man was assigned the work of placing the bolts in a single type of connection. Tightening gangs, each consisting of two men who did nothing but bring the bolts up to the specified prestress using impact wrenches, followed along immediately behind. Most of the connections could be reached without scaffolding. It was found that it took three to four men to keep ahead of a tightening gang. The average production per man, counting all of those engaged in the work, was in the order of 150 bolts per day. Two tightening gangs, confining their activities entirely to this one operation, installed as many as 3,100 bolts per working day.

When several bolts are required in a single connection, the tightening of the later bolts often increases the total clamping effect on the connection to an extent such that the first bolts tightened often have to be re-tightened. On this project it was found that connections having as

many as 7 holes in a single row could be quickly brought up to the proper tensions by tightening the center bolt first, then proceeding from the top hole down to the bottom one, thus giving the center bolt a second treatment half way through the operation.

Some 5000 high-strength bolts were used in the construction of two sections of a viaduct — one 550 feet and the other approximately 700 feet long — on the freight line of the Union Railroad Company over Turtle Creek in East Pittsburgh, Pennsylvania. This viaduct, consisting of four lines of plate girders supporting 18 inch transverse floor beams spaced 2' 6" o.c., carried track ballast laid on a steel plate deck. High-strength bolts were used to connect the floor beams to the longitudinal girders.

Over 150,000 high-strength bolts were required for the primary connections in the General Motors Corporation's huge Buick-Oldsmobile-Pontiac assembly plant at Arlington, Texas. This project, providing 1,250,000 sq. ft. of floor space, consists principally of 45' x 45', 45' x 90' and 90' x 90' bays of one story truss-and-column framing, although a portion of the building is two stories high. Overhead traveling cranes are supported on the building frame as will also be the case in the Aluminum Company's building already noted. Plans were prepared by the Argonaut Realty Division of General Motors Corporation. In the invitation to bidders, fabricators were instructed to quote on the basis of field riveting and also on the use of high-strength bolts. The successful low bidder submitted the same price for both methods of field fastening.

On some of the projects mentioned, cost comparisons were prepared covering various means of making field connections. On the others no detail studies were attempted, since even some increase in cost would have been tolerated in the interest of expediting the construction. Where comparisons have been attempted, any differences that have been found generally were so small that they could be verified only by actual performance records on two otherwise identical projects.

One item of expense, the elimination of which is the goal of research now in progress under the Council's program, has to do with the omission of shop paint at the contact surfaces of connections assembled with high-strength bolts. Section 3(c) of the Council's present Specification requires that faying surfaces be free of paint, lacquer, oil and all other materials which would interfere with the development of friction between the parts, because laboratory tests have indicated the possibility of a gradual slip under long-sustained loading, due no doubt to a shearing action within the body of the paint film. As in the case of similar provisions usually invoked where connections are to be field welded, it is necessary to note on the shop drawings all locations where the shop paint is to be omitted. This drafting room operation, coupled with some shop expense involved in marking limits for shop painting on the steel parts, and some expense in "touching up" the shop coat in the field after erection, of course, entails some cost. The expense, although not great, constitutes a challenge; some solution to the problem, other than the omission of shop paint, surely will be found.

To date the only specification recommendations published by the Research Council are concerned with the case where shear must be transmitted across a joint and where slip of any consequence generally is not permitted. For those connections where some slip can be permitted, such for example as the gradual slip associated with maximum design loads long sustained at painted contact surfaces, the continued use of ordinary unfinished bolts may offer the most practical solution. However, considerable test data is already at hand to indicate that high-strength bolt values, considerably larger than those now recommended even for rivets, might be justified if the resistance to shear of the bolt itself alone is the criterion of useful service. Such would be the case where a slip of say $1/16$ " is of little importance and the bearing area on the side of the bolt is adequate. Comparing this possibility with the present reduced values prescribed for unfinished bolts, it is conceivable that there is an economic place for high-strength bolts even where the less expensive unfinished bolts up to now have been used exclusively.

One other important use for high-strength bolts, which thus far has not been covered in the Council's Specification, is that of resisting applied tension-producing loads. Structural engineers have for many years taken advantage of the possibilities which these fasteners offer in the solution of problems of this type. It is obvious, comparing the minimum elastic proof and ultimate breaking loads specified for A-325 bolts with corresponding calculated values for rivets of the same nominal diameter, that the loss of stress area in the threaded part of the bolt is more than compensated by the superior physical properties of the bolt material, leaving a very comfortable margin of extra tension-resistance capacity per fastener.

In the absence of any accepted standards, various working values have been used by structural engineers in proportioning high-strength bolts for tension-type connections. The writers know of no case, however, where these bolts have been deliberately prestressed in tension substantially above the calculated stress which they would be required to resist in service — even though it is a well known fact that the endurance limit of bolts under cyclic loading is vastly improved when the fluctuation of stress is at a minimum.

Obviously, if some of the bolts in a connection (required to transmit "shear") are to be tightened nearly to the elastic proof load, the problem of field control of the bolt installation will be simplified if all high-strength bolts are so tightened, including those required to resist applied tension. This practice of highly prestressing bolts which are to carry tension loads in service is one which has long been recognized as beneficial in other fields of engineering. A program of static and fatigue tests on typical tension-type building connections, expected to demonstrate the beneficial effect of a high prestress, has recently been given a high priority in the Council's continuing program of research. Until such test data is in hand the Council has preferred to remain silent on the question of suitable working stresses.

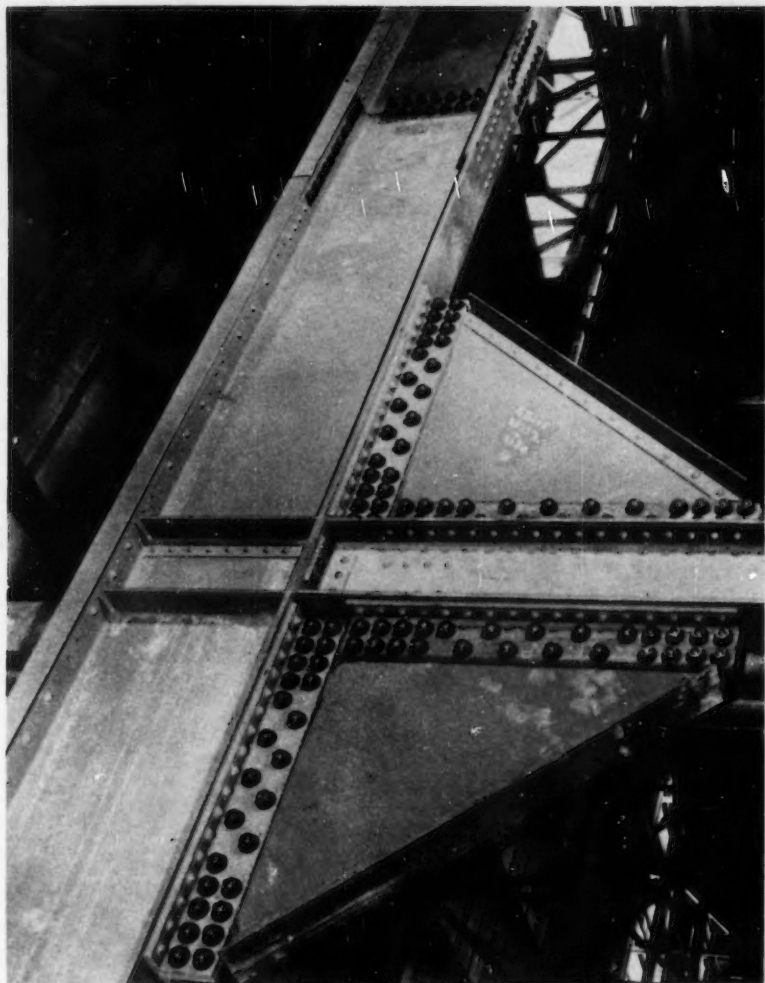


Fig. 1 High-strength bolts are used primarily at field connections. Present specification provisions are concerned only with the case where shear is transmitted across the joint.

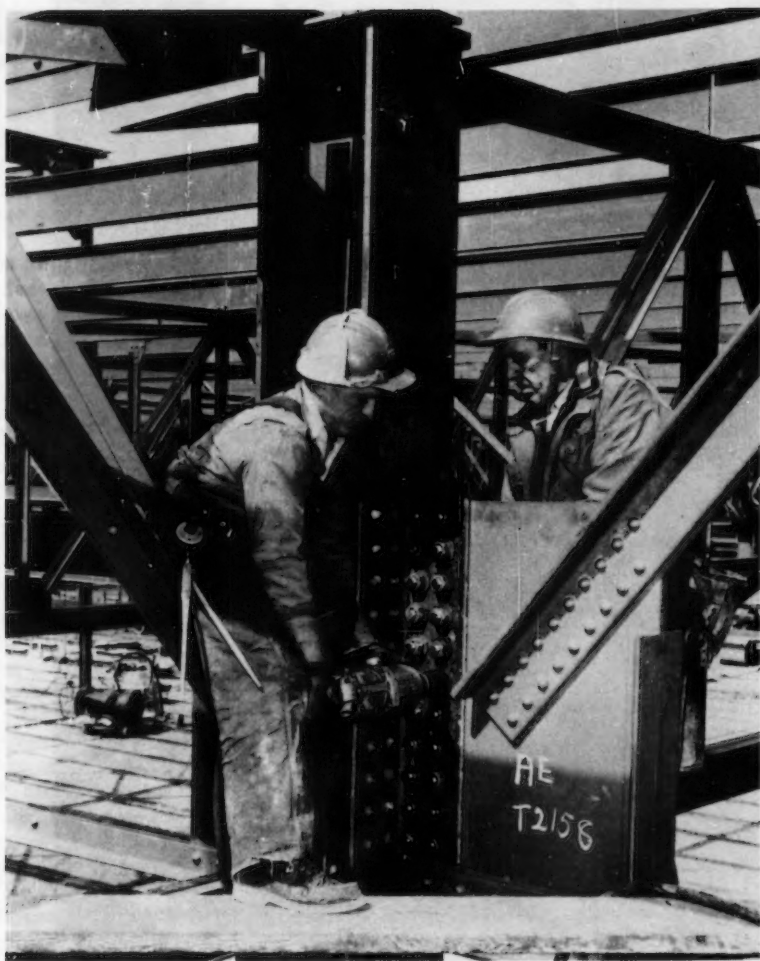


Fig. 2 Impact wrenches are slightly heavier than riveting hammers; the physical effort required of the wrench operator however, is considerably less than required of riveters.